



# Axial pile forces in piled embankments, field measurements

## Forces axiales dans les piles dans les remblais empilées, mesures sur le terrain

S.J.M. van Eekelen<sup>\*12</sup>, A. Bezuijen<sup>31</sup> and A.F. van Tol<sup>21</sup>

<sup>1</sup> *Deltares, Delft, Netherlands*

<sup>2</sup> *Delft University of Technology, Delft, Netherlands*

<sup>3</sup> *Ghent University, Ghent,*

<sup>\*</sup> *Corresponding Author*

**ABSTRACT** Several measurements were carried out in a basal reinforced piled embankment in the Netherlands. The present paper focuses on the influence of truck passages on the axial forces in the piles. The changes in axial forces in the piles were measured using two systems: (1) optic fibres attached to a square steel tube pile, measuring pile strains at ten positions along the pile length and (2) the total pressure on the pile cap with total pressure cells. Additionally, the axle loads of passing trucks and the load on the subsoil between the piles were measured. The measured changes in pile strains show that most truck load is transported to the subsoil by friction along the pile shafts. Comparison between measurements and calculations show that the truck wheel loads are spread stronger than assumed by Boussinesq.

**RÉSUMÉ** Plusieurs mesures ont été effectuées dans un remblai renforcé basal empilés dans les Pays-Bas. Le présent document met l'accent sur l'influence des passages de camions sur les forces axiales dans les piles. Les changements dans les forces axiales dans les piles ont été mesurées à l'aide de deux systèmes: (1) des fibres optiques attachés à un pieu à tube d'acier carré, mesurant souches de pile à dix positions le long de la longueur de la pile et (2) la pression totale sur le capot de pile avec un total cellules de pression. En outre, les charges par essieu des camions de passages, et la charge sur le sous-sol ont été mesurées. Les changements mesurés dans les souches de poils montrent que plus la charge du camion est transporté vers le sous-sol par frottement le long des arbres de poils. Comparaison entre les mesures et calculs montrent que les charges de roues de camion doivent être répartis plus que prévu par Boussinesq.

## 1 INTRODUCTION

Several researchers have published about research on piled embankments. Only a limited number of them presented measurements of load distributions and pile responses during the passage of a train or a truck (Van Eekelen et al., 2010, Van Duijnen et al., 2010). This is for example of importance because the truck loads need to be converted into a uniformly distributed load to be able to design the construction.

This paper reports axial load and strain measurements on a steel tube pile in a basal reinforced piled embankment. These measurements were carried out using optic fibres at 10 different depth levels and with total pressure cells on top of the pile caps. The response of the piles during truck passages will be presented in the present paper.

## 2 WOERDEN FIELD TEST

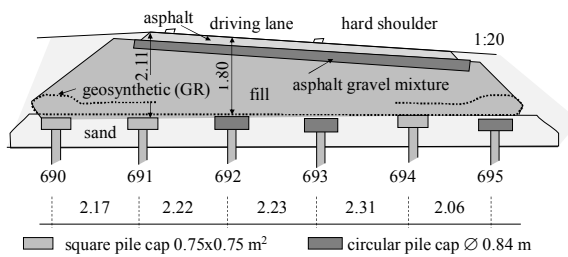
A motorway exit in Woerden, the Netherlands, was reconstructed. Part of the new road was built on a basal reinforced piled embankment. The road construction started in April 2010, and the road was opened in June 2010.

The subsoil consists of a ca. 17 m thick layer of very soft clay. The average undrained shear strength  $c_u$  along the pile shaft can be determined from the CPT in Figure 2: top-down until NAP -10 m  $c_u \cong \text{average } (q_c - u)/15 = 13 \text{ kPa}$ , until NAP -13 m  $c_u \cong 17 \text{ kPa}$ , where  $u$  is the pore pressure in kPa.

Figure 1 shows the piled embankment at the monitoring location. The system consisted of precast piles with average  $2.24 \times 2.26 \text{ m}^2$  centre-to-centre (CTC)-spacing and square  $0.75 \times 0.75 \text{ m}^2$  precast concrete

pile caps with smoothly rounded edges. On top of the pile caps lies 0.05-0.16 m sand. The geosynthetic reinforcement (GR) lies directly on the sand. The compacted fill consists of broken recycled construction material (0-40 mm), such as concrete and bricks.

A layer of PET geotextile 600/50 lies upon the sand, perpendicular to the road axis. A layer of PET geogrid 600/50 lies on top of that along the road axis. On top of the fill lies 0.25 m asphalt granular material mixture and 0.18 m asphalt. Van Eekelen et al. (2012, 2015a,b,c) describe the monitoring program. The present paper presents measured axial pile loads.



**Figure 1.** Monitoring area. Piles are precast piles except piles 693 and 695, which are square steel tube piles.

### 3 MEASUREMENTS

#### 3.1 Pile strains

Four long glass fibres, with each 10 strain sensors, were attached to each side of pile 693 to measure pile strains. The fibres were protected by casting them into a resin. The purpose of the optic fibres was to be able to calculate the bending pile moments in the pile from the measured pile strains. Therefore, pile 693

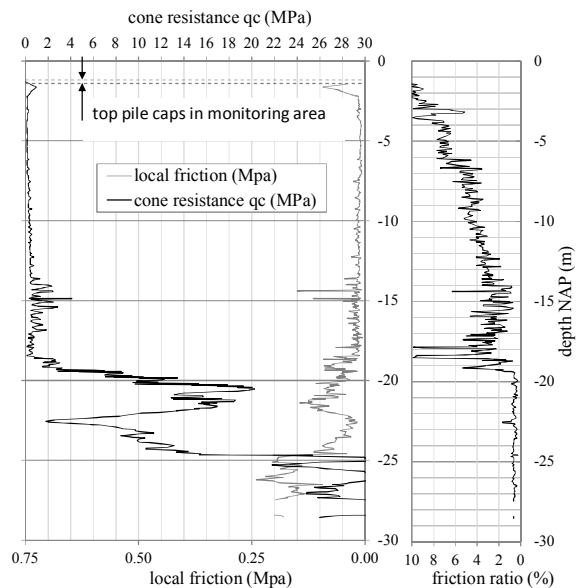
was not a precast concrete pile, but a square steel tube pile, specified in Table 1. This was done to be sure about the section modulus of the pile, which is necessary to calculate the pile moments.

**Table 1.** Square steel tube pile 693, properties and optic fibres.

Width	$b$	mm	300	
Thickness	$d$	mm	8	
Length	$l$	m	24	
Area	$A_{tube}$	mm <sup>2</sup>	9275	
Young's modulus	$E$	N/mm <sup>2</sup>	2.10E+05	
Weight	$G$	kg/m	72.8	
Moment of inertia	$I_x=I_y$	mm <sup>4</sup>	1.31E+08	
Section modulus	$W_x=W_y$	mm <sup>3</sup>	8.75E+05	
Depth pile cap surface		NAP <sup>a</sup> m	-1.36	
Asphalt surface		NAP <sup>a</sup> m	+0.50	
Distance to neighbouring piles:				
	North	m	2.31	
	West	m	2.21	
	South	m	2.23	
	East	m	2.28	

<sup>a</sup> NAP: Dutch reference level

Due to problems with the optic fibre measurements, only the changes in pile strains due to truck passages can be presented in the present paper.



**Figure 2.** Typical CPT at the monitoring location

### 3.2 Axle loads of passing trucks

The weight of the axles of passing trucks was measured using weigh-in-motion devices (WIM) with pressure sensors, installed in the asphalt at two locations. Each WIM measured the truck velocity and configuration and the weight of each axle twice.

Table 2 gives the measured geometry and weight distribution of the considered trucks. These measurements were carried out on June, 12<sup>th</sup>, 2012, which is more than two years after opening the road. The ground water on that day was at 0.06 m below the pile cap surface of pile 693. It should be noted that the standard deviation of the four axle load measurements is ca. 25% of the measured load. This large standard deviation is probably caused by a limited accuracy of the WIM devices.

**Table 2** Considered trucks.

		1339a	1339b	1354	1355	1405a	1405b
velocity	km/h	58	56	49	47	45	64
Length	m	16.15	11.00	9.77	15.94	18.00	8.78
truck							
Standard deviation	mm	17	<sup>a</sup>	17	16	9	11
length							
Number of axles	-	6	3	2	4	5	3
Distance to axle 1							
axle 2	m	2.62	1.70	5.74	3.69	3.80	4.18
axle 3	m	3.91	5.15		10.36	7.66	5.95
axle 4	m	9.64			12.31	13.36	
axle 5	m	10.94				14.66	
axle 6	m	12.44					
Total weight	kN	283	360	189	307	768	298
Standard deviation	kN	67	<sup>a</sup>	47	73	163	86
total weight							
Weight							
axle 1	kN	68	132	62	62	89	94
axle 2	kN	56	124	127	69	163	120
axle 3	kN	55	104		104	195	85
axle 4	kN	35			72	176	
axle 5	kN	35				145	
axle 6	kN	35					

<sup>a</sup> total weight and configuration of truck 1339b has been provided by truck owner.

### 3.3 Load distribution

The total load on pile 693 (and pile 692, not presented in the present paper) was measured on the pile cap, below the geosynthetic reinforcement, as described by Van Eekelen et al. (2012, 2015a,b). For this purpose, the square pile cap was replaced by a circular one. This made it possible to apply a using a total pressure cell (TPC) with the same diameter (0.85 m) as the pile cap. However, a smaller wooden plate of 0.75 m diameter had to be applied between the TPC and the pile cap because of the relatively stiff edges of the large TPC.

Converting the pressure (in kPa) measured within the TPC into a force (in kN) can be done two ways: using the TPC diameter (maximum interpretation) or using the diameter of the wooden plate (minimum interpretation). Figure 3 to Figure 7 give both results. Figure 9 gives the average of these two values.

The pressure underneath the GR at locations G23 and G38 (Figure 1) was also measured with TPCs.

## 4 RESULTS MEASUREMENTS

Figure 3 to Figure 7 show the measured axle loads, the changes in pile strains  $\Delta\epsilon$  and axial forces  $\Delta N$ .

An off-set (non-zero start value) was applied for the pile strains. This makes it possible to see the differences between the different strain gauges.

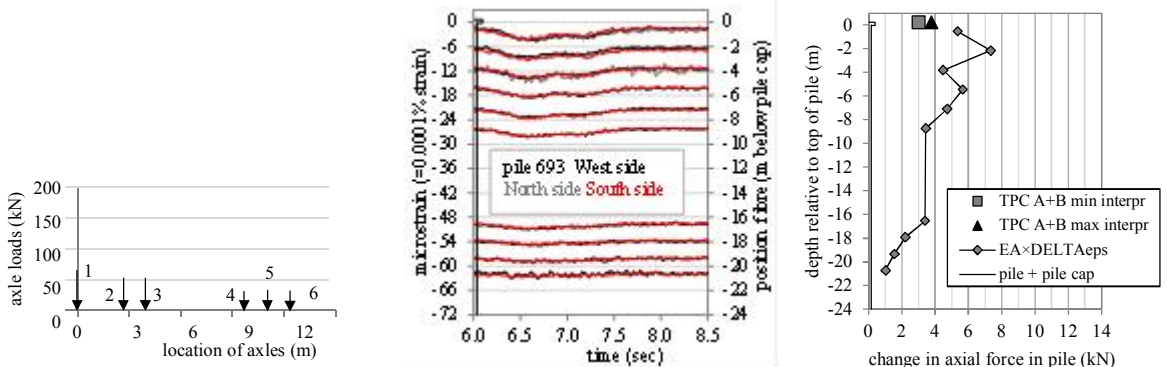
The maximal axial force increments  $\Delta N$  shown in the figures were calculated from the maximal measured pile strain increments, using  $\Delta N = EA_{tube} \cdot \Delta\epsilon$ , where the values of  $E$  and  $A_{tube}$  are given in Table 1.

The measurements show that deeper strain gauges measure smaller pile strain responses to the passing trucks; the truck load is almost completely transferred to the soft soil around the pile by means of friction along the pile shaft. Only a very limited amount of the pile load reaches the toe of the piles.

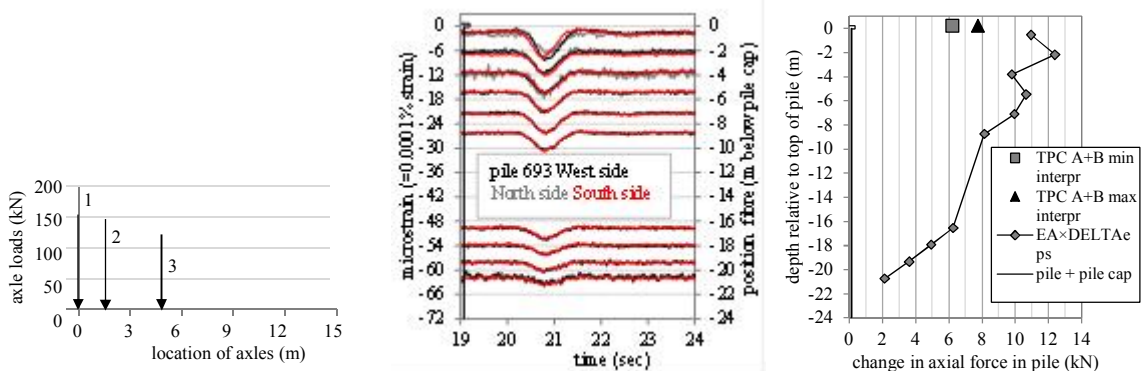
These measurements should agree with the undrained shear strength  $c_u$  (kPa) of the subsoil, which was determined in section 2. Consider truck 1339b. The measured average strain along the pile shaft is 4 microstrain. For a 20 m long pile this gives an elongation of  $-4 \cdot 10^{-6} \cdot 20 = -0.08$  mm. We have seen that the friction behaviour along the pile shaft is dominant to the pile toe, and therefore it can be assumed that 1 mm displacement of a pile activates 50% of the max-

imum pile shaft friction (NEN, 2011). Thus -0.08 mm elongation approximately activates 4% of the maximum pile shaft friction. The maximum activated shaft friction is equal to the measured maximum axial force: 12 kN (Figure 4) as the pile toe barely feels the truck passage. The maximum pile shaft friction

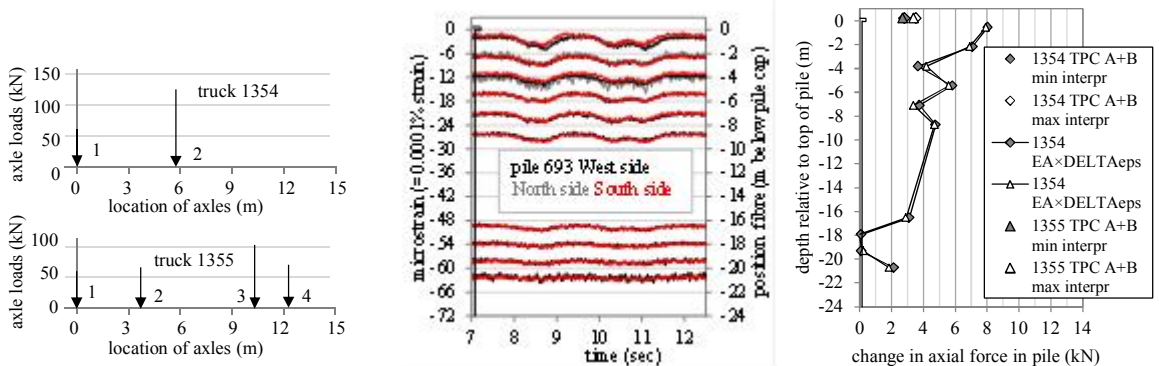
will therefore be:  $12 \text{ kN}/4\% = 300 \text{ kN}$ . The area of the pile shaft is  $20 \text{ m} \cdot 4 \cdot 0.3 \text{ m} = 24 \text{ m}^2$ . The undrained shear strength  $c_u$  lies thus around  $300 \text{ kN} / 24 \text{ m}^2 = 12 \text{ kPa}$ , which indeed is in the range of  $c_u \approx 13 \text{ kPa}$  that was determined in section 2.



**Figure 3.** Truck 1339a: a. axle loads b. measured pile strains c. axial pile force at the maximum value of the highest strain gauge, (results of TPCs and measured pile strains).



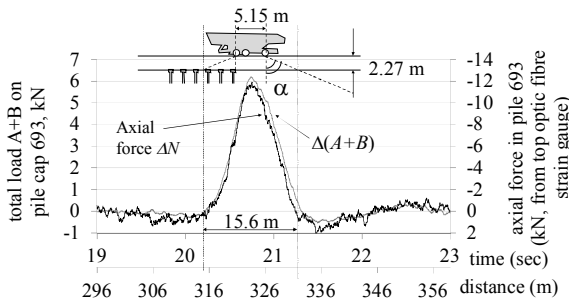
**Figure 4.** Truck 1339b: a. axle loads b. measured pile strains c. axial pile force at the maximum value of the highest strain gauge, (results of TPCs and measured pile strains).



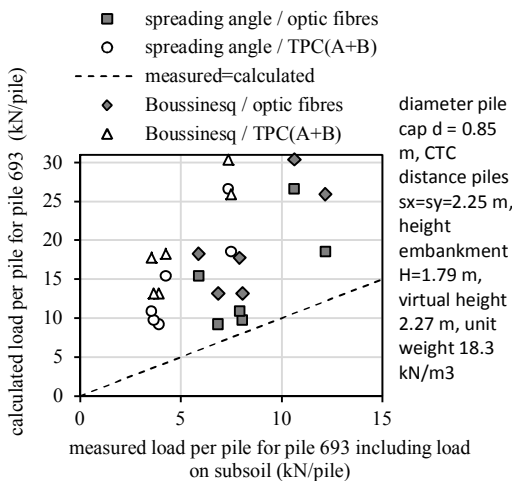
**Figure 5.** Truck 1354 and 1355: a. axle loads b. measured pile strains c. axial pile force at the maximum value of the highest strain gauge, (results of TPCs and measured pile strains).



better with the measurements than the load distribution assumed by Boussinesq.



**Figure 8.** Axial force determined from strain measured with optic fibre 0.53 m below pile cap and pile load A+B measured with TPC (minimum interpretation). On top: determination of spreading angle of axle load of truck 1339b load.



**Figure 9.** Calculated and measured change of total load on pile 693 due to truck 1339b. TPC (A+B) is the average of the minimum and maximum interpretation.

## 6 CONCLUSIONS

Truck passages give changes in axial pile forces in a basal reinforced piled embankment. These changes were measured using (1) optic fibres attached to the square steel tube piles, measuring pile strains at ten positions along the pile shaft and (2) total pressure cells on the circular pile caps. Additionally, the axle loads, truck configurations and the load on the subsoil were measured.

The measured pile strain changes show a decrease with depth. The pile toe barely feels the truck. This shows that most truck load is transported to the subsoil by friction along the pile shafts.

For design purposes it is necessary to convert a passing truck into a uniformly distributed load. Two calculation methods are described and compared to the measurements: a Boussinesq-based method and spreading each wheel load with a spreading angle of  $67^\circ$ . This value followed from the truck velocity and time that the truck is felt by the pile. The spreading calculations agree better with the measurements than the load distribution assumed by Boussinesq.

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